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AUTOMATED REPAIR OF PRINTED WIRING ASSEMBLIES

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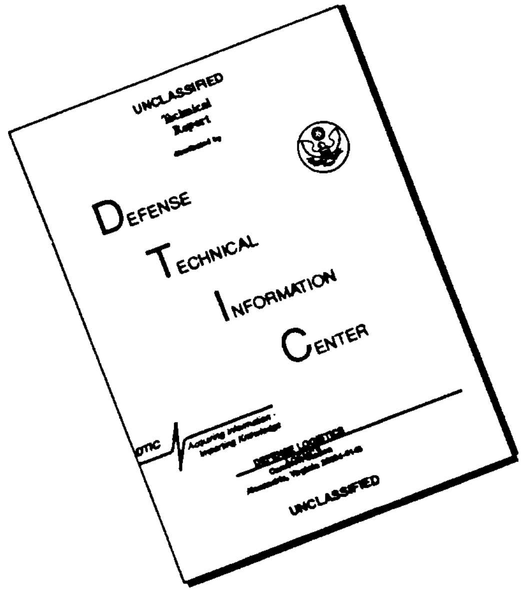
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13. ABSTRACT

The objective of the Repair Technology for Printed Wring Assemblies (PWA) program (sponsored by the U.S Air Force on contract F33615-91-C-5700) was to design, fabricate, test, install, and validate an automated modular system for the repair of printed wiring assemblies. In its final form, the system will consist of six modular stations that will identify and target the failed PWA components, identify and remove conformal coatings, remove the failed components, replace and solder the new components, and provide an operator assisted means for visual inspection. The first three stations were fabricated, tested, installed and validated at Warner Robins Air Logistics Center in Warner Robins, GA. The remaining stations may be completed under a separate Air Force contract.

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Conformal Coating, PWA Repair, Repair Technology (REPTECH), Sustainment, Printed Wiring Assemblies (PWAs), Surface Mount Devices (SMDs), Plated Through Hole (PTH), Fourier Transform Infrared (FTIR) Spectroscopy, WR-ALC.

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1. SUMMARY

1.1 Background

Each year thousands of hours are spent in the repair of Printed Wiring Assemblies (PWAs). The repair of PWAs, and more specifically the need to identify and remove conformal coatings followed by replacement of defective components on PWAs, has traditionally been performed using manual skills and techniques. As the complexity of PWAs continues to increase i.e., higher density, finer pitch and larger size integrated circuit components, the skill required to replace defective components is also increasing, to the point where manual replacement is essentially precluded. While commercial PWA rework equipment is available, these stations have limitations since they are semi-automatic and therefore require a high degree of manual dexterity. They require the operator to manually place the PWA into the station, insert and position the desired end-effector (such as hot gas, resistance, or IR heating tools), and lift the desoldered component with a vacuum wand. Just as there are limits to the manual capability of using a soldering iron for component removal, there are limits to the effectiveness of a semi-automatic rework station as the component and lead densities increase and the line spacing decreases. In addition, current commercial rework stations only address a subset of the total repair process (i.e., they do not perform conformal coating identification and removal, they cannot remove components held down with adhesive, they do not apply solder past, etc.). While these commercial rework stations have a role to play, they do not solve the substantive problem associated with the ever increasing PWA complexity, because they rely on variable operator skills. This variability seriously impacts the consistency of process quality. Traditional methods have relied on chemical means for the identification of conformal coatings and then removal of these coatings with further chemicals or uncontrolled abrasive blasting. With the health hazards associated with the use of chemicals and the dangers of damage to the PWAs, it has become important to consider a fully automated system that could provide consistent, reliable, high quality repairs while at the same time provide an environmentally safe workstation. Westinghouse, under contract with Wright Patterson Air Force Manufacturing Technology Directorate, has developed this automated repair facility.

1.2 Summary

The objective of the Repair Technology for Printed Wiring Assemblies program (sponsored by the U.S. Air Force on contract F33615-91-5700) was to design, fabricate, test, install, and validate an automated modular system for the repair of Printed Wiring Assemblies. In its final form, the system will consist of six modular stations (See ***Figure 1***) that will identify and target the failed PWA components, identify and remove conformal coatings, remove the failed components, replace and solder the new components, and provide an operator assisted means for visual inspection. The first three stations (Component ID/Targeting and Coating ID, Coating Removal, Component Removal: See ***Figure 2***) were fabricated, tested, installed and validated at Warner

Robins Air Logistics Center in Warner Robins, GA. The remaining stations may be completed under a separate Air Force contract.

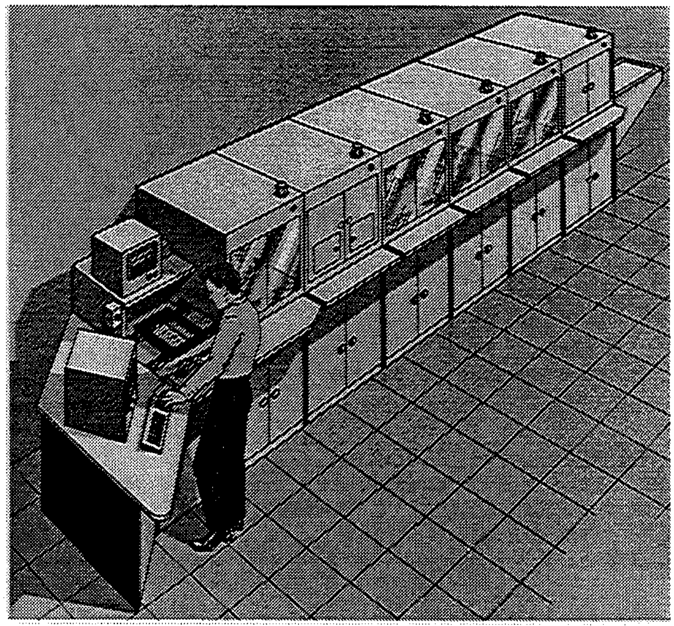

Figure 1. Automated Repair Facility for Printed Wiring Assemblies

The PWA Repair Facility operates in the following manner:

A PWA, to be repaired, is hand loaded into a universal locating fixture which is then placed on a conveyor system that indexes it through the repair stations, each performing a particular part of the repair process. The repair process is initiated by the operator identifying the component to be replaced (the failed component has been diagnosed by prior independent testing, not as part of this system) and interactively targeting its location. The system then processes the PWA, precisely measuring the height of the PWA surface and top of the failed component. The conformal coating is identified and placed into one of five generic categories. The coating is selectively stripped away from the component's solder joints. The component is desoldered and removed. These operations are completed in the first three stations. In the remaining stations, the PWA is prepared for solder paste deposition; solder paste is applied and inspected and if required, an adhesive is deposited. The new component is then checked for lead alignment and coplanarity and is precisely placed on the solder paste. Each lead is individually laser soldered and an enlarged view of the leads is displayed to assist the operator in the inspection process.

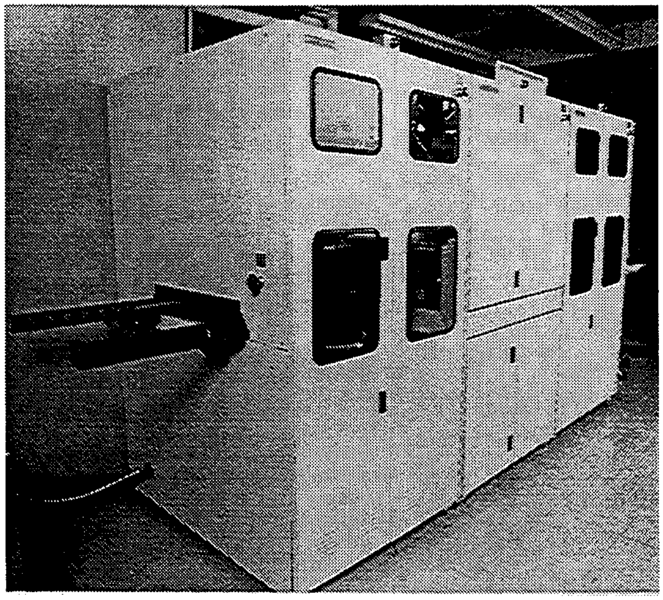

Figure 2. Stations 1,2, and 3 Installed at Warner Robins ALC.

2. TECHNICAL DISCUSSION

This section describes the key technical issues that were solved in the development of the Printed Wiring Assembly Repair Facility.

2.1 Problem Statement

The objective of this program was to build an automated system that could replace defective components on Printed Wiring Assemblies (PWAs). The characteristics of the components (high lead density, fine pitch, large size) and construction of the PWAs (use of conformal coating, components bonded to PWA with adhesive, design for cooling) makes manual repair of the PWA very difficult or impossible even with the use of semi-automatic commercially available rework stations.

2.2 Key Technical Issues

There were several key technical issues that had to be addressed in order to make in the PWA Repair Facility a viable system. These issues are summarized below:

1. The design specifications, for the manipulators and fixture locating system, dictated that they must have a high degree of accuracy. The PWA must be positioned to within ±0.001" from station to station. The accuracy specification, of the manipulators, ranged from ±0.001" to ±0.010" depending on the station. Even though automatic machine vision systems were used to measure component locations (and other features) on the PWA, they did not make use of any fiducial marks since few, if any, of the PWAs to be processed by the system, have these marks. This is in contrast to commercial systems which use vision systems and the fiducial marks to achieve their positioning accuracy.
2. An effective and reliable method for conformal coating removal had to be developed that did not have the usual detrimental effects (harmful to the operator, harmful to the environment, damage the PWA). This is in contrast to traditional manual methods of conformal coating removal which include scrapping with tools, using harsh chemicals (solvents), or uncontrolled abrasive blasting, which have these shortcomings.
3. An effective and reliable method for removing components, bonded to the PWA with adhesive, had to be developed that did not damage the PWA and minimized or eliminated damage to the component. Commercially available rework stations or pick-and-place machines, using suction devices, do not have any capability to lift components bonded with adhesive. Traditional manual methods to lift these components, such as prying or twisting with hand tools, are prone to damaging the PWA and component.

2.2.1 PWA - Definition And Description

A Printed Wiring Assembly (PWA) is a module containing one or two printed circuit boards (Polyimide or FR4) containing surface mount and through-hole components, connectors, and mounting brackets (See ***Figure 3***). Many types of PWAs also contain a core designed to facilitate thermal cooling. PWAs range in size from 1.5" x 1.5" to 16" x 18" with a maximum thickness of 2". The PWA core types handled by the PWA Repair Facility are described below:

1. **SINGLE SIDED** - A single board with components on one side.
2. **DOUBLE SIDED** - A single board with components on two sides.
3. **AIR CORE** - A two board assembly with a honey-combed air space, between the boards, used for cooling.
4. **METAL CORE** - A two board assembly with a metal heat sink, between the boards, used for cooling.

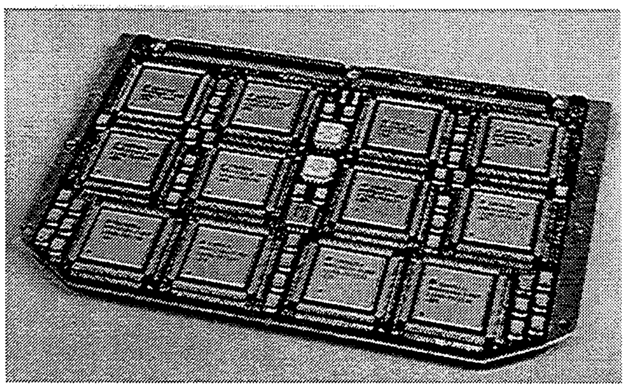

Figure 3. Typical Metal Core Printed Wiring Assembly.

2.2.2 Component Sizes And Types

The PWA Repair Facility can process components with a body size ranging from .05" x .1" to 2.0" x 2.0" (2.5" x 2.5" including leads), and with a height range of .061" to .5". Components must have a maximum of 400 leads, a minimum lead pitch of 20 mills, and the minimum spacing between devices is 40 mills. The system can automatically process the following surface mount devices:

- Leaded chip carriers including Plastic Leaded Chip Carriers (PLCC), Small Outline Integrated Circuits (SOIC), Quad Flat Packs (QFP), and Ceramic Quad Flat Packs (CERQUAD) both with gull-wing leads and J-leads
- Leadless Chip Carriers (LCC)
- Surface mount resistor arrays
- Capacitor arrays

The PWA Repair Facility can semi-automatically process the following through-hole devices:

- Pin Grid Arrays (PGA)
- Dual In-line Packages (DIP)

2.3 Damage Minimization Concerns

The average cost of a LANTIRN PWA is approximately $15,300, and PWAs in other systems average approximately $37,300 (some can exceed $300,000). Therefore, minimizing damage to the PWAs is a major characteristic of the PWA Repair Facility. Many of the manual repair methods, such as coating removal with harsh chemicals or using scrapping tools, prying off the component with a screw driver, twisting off a component with a clamping tool, can cause damage to the PWA. Because of this, the following features were designed into the Repair Facility:

- The micro abrasive blasting operation, used for conformal coating removal at Station 2, uses precise computer control of an iterative process of blasting and examination, to eliminate concerns of damage to the PWA. The abrasive media was carefully chosen for its aggressiveness to effectively remove all of the coating from the designated areas, and yet cause no damage to the PWA surface. The anit-static quality of the media and of the blasting operation eliminates damage concerns to adjacent components on the PWA.
- The gripping jaws, used at Station 3, were designed to provide enough lifting force to break the adhesive bond between the component and the PWA, and yet do not contact the PWA surface or apply an opposing force to it, as does manually prying the component with a screw driver.
- Prior to processing by the Repair Facility, operators use diagnostic systems to identify failed components on the PWA. This diagnostic system often produces a list of more than one possible defective component. The gripping jaws, used at Station 3, were designed to minimize or eliminate damage to the component to be removed. This way, the removed component can be tested in a stand-alone mode to confirm its operational condition.
- The desoldering system, at Station 3, was designed to deliver precise amounts of energy to the component to be removed. This strict control is needed so that the conditions for successful removal (solder at all leads is liquefied, and adhesive bond is broken down) and yet no damage to the PWA occurs. Damage, such as PWA substrate charring or delamination, can occur if too much energy is applied to the component. If too little energy is applied, not all of the solder joints may liquefy. In this case, when the component is lifted, a solder pad may be lifted from the PWA surface.

3. PROGRAM DESCRIPTION

3.1 Program Preliminary Activities

3.1.1 Needs Analysis

Westinghouse contracted with Applied Concepts Corporation to execute much of the needs analysis in order to provide some independent objectivity to the process. The following list summarizes the conclusions of the study done by Applied Concepts (See document "Economic Analysis of Printed Wire Assembly Repair at WR-ALC/LY" CDRL 010 by Applied Concepts, January 8 1992).

- The complexity of integrated circuit components used on PWAs repaired by WR-ALC has increased to a point where existing manual replacement techniques very soon will not be sufficient.
- Semi-automated rework stations will extend replacement capability, but they are too limited in their capability to replace complex components. They will help, but not solve the fundamental problem.
- There are several systems slated for repair at WR-ALC that have components requiring advanced automation for component replacement.
- Four of these systems have workloads that were defined at the time the needs analysis was conducted are:
    - LANTIRN (Navigation and Targeting Pods)
    - APG-70 (Fire Control System Radar)
    - APQ-175 (Adverse Weather Aerial Delivery System)
    - APQ-170 (Combat Talon II)
- These four new systems will impose a new workload of approximately 6,200 PWAs per year onto an existing current workload of approximately 72,000 PWAs per year. There may be other advanced and complex systems with potentially nonrepairable PWAs assigned to WR-ALC for repair in the future including J-STARS and others.
- With current manual or semi-automated rework stations, replacement of complex components (components with greater than 60 leads, or with lead pitch less than 0.035") causes significant deterioration in quality, if replacement can be performed at all. For the most part, PWA failures caused by complex components, will be scrapped.

The following conclusions use extremely conservative figures.

- The percentage of "PWA repair hours" to "total system repair hours" is constant for all systems (16.5%)

- All PWAs require an average of 4.8 hours to repair. This indicates test, repair, and re-test.
- The percentage of PWAs with complex devices requiring automated component replacement techniques is the same for all systems (16%).
- The percentage of failures/repairs caused by complex devices is a constant 5% for all PWAs.
- The number of LANTIRN PWAs that would be scrapped due to a failure in a complex device is 38. With the average cost of a replacement PWA for LANTIRN being $15,328, the total cost to replace LANTIRN PWAs is $582,464 per year.
- The number of APG-70, APQ-170, and APQ-175 PWAs that would be scrapped due to a failure in a complex device totals 12. With the average cost of a replacement PWA for these systems being $37,315, the total cost to replace these PWAs is $447,780 per year.
- **As an absolute minimum, under present costs, over $1,000,000 per year in PWA replacement costs will be incurred due to the inability to repair PWAs in these systems! Replacement PWAs in the future will be considerably more expensive. Being able to repair as few as 50 PWAs per year justifies the cost of a fully automated repair facility. In addition, the facility can provide consistent, high quality automated repair to many thousands of PWAs.**

3.1.2 Process Analysis At Warner Robins Air Logistics Center

The process analysis conducted at WR-ALC concluded that while the system will semi-automatically handle through hole devices, the development of the system should concentrate on full automation of the repair process for surface mount devices. It was further concluded that large, bulky components (such as capacitors, inductors, transformers, etc.) and all devices with small lead count would be repaired manually. Finally, Warner Robins asked that a monitor be added to each station where a camera is present. This feature will allow the operator (and any observer) to monitor the process of that station. Westinghouse complied with this request by installing a video switch on the monitor at the operators console. This allows the operator to stay at one location and view the image from the cameras at all stations.

3.1.3 Methodology For Coating ID

During the preliminary design phase of the program, several conformal coating identification experiments were done. Two methods, Specular Reflectance-FTIR and FT-RAMAN, were evaluated (See document "Informal Technical Information" (CDRL 001) "Process Experiment: Conformal Coating Identification", November 27, 1991). Personnel from WR-ALC were concerned about people's fingerprints (i.e., oils in the skin) on the surface of the PWA interfering with the coating ID process. Specular Reflectance-FTIR was selected because it was shown that the presents of "oily fingerprints" on the surface of the PWA had little significance on this method. This is because the oil from skin displays typical aliphatic hydrocarbon bands (akin to parafinnic oil) which would be quite

distinctive and, in most cases, be substantially removed from the main absorption bands shown by the five generic conformal coating materials.

FTIR Spectrometers from Nicolet and MIDAC were evaluated. A MIDAC M-Series FTIR Spectrometer with Axiom SRX-332 nitrogen-cooled detector were selected. These two subsystems are coupled by a telescoping IR beam delivery system that is purged with nitrogen to keep it free from contaminants (See ***Figure 16***). Under software control, the spectrometer compares the specular reflectance data, of the coating to be measured, with the data sets listed in its reference library. It then returns a result, which is the generic category of the coating in the library that is the best match to the measured coating. The reference library was developed with multiple samples of each type of coating in each on the five generic categories. The samples came from various manufactures such as Chase Corporation, General Electric, Dow Corning, etc. The coating samples were applied by dipping, brushing, spraying, and vacuum deposition. The cure procedures included drying at room temperature, drying at elevated temperature, moisture activated, UV, and 2-component system (2-part epoxy). This provided a broad range of coating circumstances that the Repair Facility were likely to encounter at WR-ALC.

In addition, the specular reflectance data varied depending on material underneath the coating. At Station 1, the coating ID point is placed on the top of the component to be removed. Therefore, the coating samples were applied to component surfaces which included ceramic, ceramic with gold lids, and black plastic. The reference library included specular reflectance "signatures" for each combination of specific coating type, coating category, and component material.

3.1.4 Methodology For Coating Removal

During the preliminary design phase of the program, several conformal coating removal methods were evaluated. These included: laser stripping, water jet (with and without abrasive), and dry abrasive blasting. Laser stripping caused the coatings to char, and removing the char damaged the PWA. Water jet removal with abrasive was too aggressive and caused damage to the PWA. Water jet without abrasive was not effective on the harder coatings such as epoxy and polyurethane. Dry abrasive blasting proved to be the most effective in removing each type of coating. Several blasting media were evaluated. These included wheat starch, sodium bicarbonate, walnut shells, and a plastic media. However, the blasting operation caused an electro static charge buildup that could exceed 3000 volts causing damage to the other components on the PWA. Several methods of reducing or eliminating the this problem were evaluated. Use of electronic ionizer bars and grounded floor mats within the micro-blaster enclosure reduced static levels by 75% or more. However, this was insufficient to provide protection to the most sensitive devices on the PWAs. Use of an in-line nuclear ionizer charged with 10 millicuries of Polonium-210 was found to be ineffective. Wheat starch treated with an anit-static solution proved to be most promising. However, the best results were achieved with a plastic blasting media with the anti-static treatment applied by the manufacturer. The medium consists of a plastic powder abrasive (40/60 mesh) treated with Cyastat Sn (American Cyanamid Co.) anti-static compound. This material effectively controls, to acceptable levels (less than 25 volts), the charge that can be generated in this method of coating removal. To reduce the amount of blasting material accumulating on the PWA, a vacuum system is incorporated into this station. To eliminate any static

buildup associated with the flow of air, an ionizer is placed in the air stream drawn over the PWA.

3.1.5 Methodology For Solder Reflow

The desoldering process, at Station 3, was developed using a Conceptronic Pulsar II Rework Station. Parts of this same station were later incorporated into the hardware at Station 3. Heat energy is supplied by a xenon light source that generates a focused collimated IR beam. The heat level and time period for that level can be manually set on the Conceptronics station. Desoldering is accomplished by applying various heat levels and time periods in successive steps. The area, to be heated, is adjusted by manually inserting different size apertures.

As stated in Section 4.4, the desoldering process used at Station 3, involves two heat cycles (two software controllable heat energy levels and time periods). The first cycle, Preheat, operates at a reduced heat energy level. It is used to allow the temperature of the PWA to rise within prescribed limits to minimize thermal stresses to the PWA. The second cycle, Reflow, operates at a greater heat level. It is used to achieve solder reflow on all leads and to breakdown the adhesive bond. Through experimentation, it was found that the PWA Core Type (See Section 2.2.1) and size of the component determined the length of time of each step. The sizes were divided into three categories, small (components up to 0.5" x 0.5"), medium (components between 0.5" x 0.5" and 1.0" x 1.0"), and large (components between 1.0" x 1.0" and 2.0" x 2.0").

The desoldering parameters (length of time and heat energy levels) were developed for various PWA Core Types and component size categories, and stored in the database. Their values can be edited, and new parameters can be added as new component and PWA configurations are encountered (See Section 4.1.1). When the desoldering operation begins, at Station 3, the heat cycles are automatically implemented by the control computer. In addition, the computer automatically adjusts an aperture to match the size of the component in any rectangular outline, so that only the defective component encounters high heat. This is an important difference between manual rework stations and the PWA Repair Facility. Manual rework stations have only limited ability to resize the area to be heated, usually round or square shapes in fixed sizes. This allows heat to be applied to other components, in the local area of the defective component. Components, heated unnecessarily, can be damaged or experience degraded solder joint integrity.

3.1.6 Methodology For Component Gripping

Early in Phase II, System Fabrication, it was clear that components, bonded to the PWA with adhesive, could not be lifted using the conventional vacuum suction devices found on most manual rework stations. Tests were conducted using a makeshift "heavy-duty" vacuum suction device that generated several pounds of pull force, however this also proved inadequate in removing components with adhesive. It became clear that a mechanical means of grasping and lifting the component was necessary. This grasping and lifting system needed to apply forces on the component similar to the way an operator uses a small screw driver with prying and twisting motion at one corner of the component in order to remove it manually. However, the automatic gripping mechanism must eliminate damage to the PWA, and reduce or eliminate damage to the

component. This mechanism must also be capable of applying enough lifting force to remove the largest, 2.0" x 2.0" components (worst case).

A Cured Adhesive Pull Test was conducted using 1.0" x 2.0" and 2.0" x 2.0" dummy components, raised to 200° C. The components required between 24 to 34 lbs. eccentric pulling force to break the bond of the most tenacious adhesive. A Friction Grip Test and a Chip Splitting Test were also conducted. Measurements of the static coefficient of friction ranged from 0.28 to 0.43 for ceramic components. Maximum jaw force is in the range of 110 to 140 lbs., which when considering the friction coefficient, will be able to provide enough force to remove the 2x2 components. Measurements of the splitting force ranged as high as 57 lbs. with no damage to the component. It was concluded that the worst case component (2x2) bonded with adhesive, can be gripped and removed using forces well below the forces necessary to cause splitting.

The end-effector, used at Station 3, includes the automatic component gripping mechanism that meets all of these requirements. The mechanism consists of a set of jaws that grasp the component at diagonal corners. There are two styles of jaws that are manually interchangeable. One style fits components that have notched corners (Ceramic Quad Flat Packs) and does not damage any of the components leads. The other style of jaw fits all other components with square corners, and does damage some of the leads during gripping. In either case, the jaws do not damage the PWA. When the controller, for the Station 3 robot, senses that the maximum gripping force has been obtained, it then lifts at one corner while allowing both jaws to pivot. This provides the eccentric pulling force that breaks the adhesive bond and allows the component to be removed.

The jaw tips contain electric heating elements that are used to heat the tips to a temperature in excess of solder melt temperatures (approximately 220° C). This is necessary so that when the jaws come in contact with the component, they do not act as a heat sink cooling the component leads, near the gripping corners, below solder melt temperatures. This would interfere with a consistent and reliable desoldering and lifting operation.

3.2 Preliminary Design

The various tasks in this phase are outlined in the following sections.

3.2.1 System Architecture And Specifications

The PWA Repair Facility is composed of several modular stations and controlling subsystems (See ***Figure 4***). Master control of the repair process resides with the supervisory system located at Station 1. This system is a multi-tasking computer (Sun SPARCstation IPX running UNIX) that supervises and monitors the overall repair process. Each repair station is also equipped with its own dedicated process control computer (also Sun SPARCstation IPXs running UNIX). The supervisory system, using X-windows for the user interface, is the main interface through which the operator initializes and monitors the repair process. All stations are equipped with ETHERNET network communications using TCP/IP protocol. The hardware specifications, for each station, are listed in the following subsections.

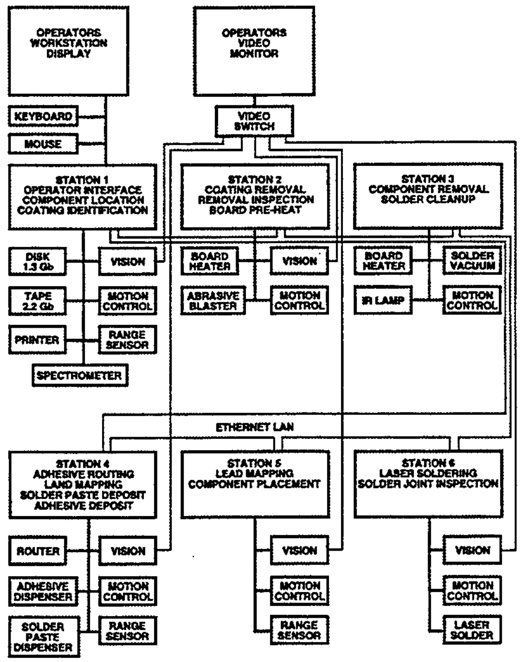

Figure 4. Block Diagram of PWA Repair Facility.

3.2.2 Supervisory Computer Hardware

- Sun Microsystems SPARCstation IPX
- 16 MB RAM
- 424 MB internal hard disk
- 1.44 MB floppy disk (3.5 inch)
- 19 inch color monitor with mouse
- File server option, which includes:
  - ♦ 1.3 GB hard disk
  - ♦ 2.3 GB 8mm tape
  - ♦ 644 MB CD ROM
  - ♦ ETHERNET network communications with TCP/IP protocol
  - ♦ Network File System (NFS) for remote file access. Each station can access a file on the supervisor's disk as if it were resident on its local hard drive.
- VGA color monitor (used to display camera images from Stations 1 and 2.
- Black Box 2-way VGA switch.

3.2.3 Station 1 Hardware

- The Supervisory Computer is used.

- A VMEbus chassis contains the following items:
  - ♦ Datacube MaxVideo 20 and Digicolor image processors
  - ♦ Delta-Tau Systems Inc. 4-axis motion control card
- Two CCD cameras with fluorescent light source
- A Delta-Tau Systems Inc. 100-watt 4-channel servo amplifier
- Cyberoptics Point Range System (PRS) non-contact laser sensor
- MIDAC M-Series FTIR Spectrometer with Axiom SRX-332 nitrogen-cooled detector.
- A Texas Microsystems 80386 PC/AT. This computer controls the Cyberoptics laser measurement system and the MIDAC spectrometer.
- Three CMC DC servo motors.
- 3-Axis manipulator mounted on a rugged metal frame
- Conveyor subsystem

3.2.4 Station 2 Hardware

- Sun SPARCstation IPX, 16 MB RAM, 207 MB hard disk
- A VME chassis contains the following items:
  - ♦ Datacube MaxVideo 20 and Digicolor image processors
  - ♦ Delta-Tau Systems Inc. 4-axis motion control card
- CCD camera with both fluorescent and ultraviolet light sources
- A Delta-Tau Systems Inc. 100-watt 4-channel servo amplifier
- A 2-position air cylinder which controls the position (either 0° or 45°) of the abrasive blasting nozzle.
- Torit dust collector model VS550
- Electronic air ionizer system
- Four CMC DC servo motors
- 4-axis manipulator mounted on a rugged metal frame
- Conveyor system

3.2.5 Station 3 Hardware

- Sun SPARCstation IPX, 16 MB RAM, 207 MB hard disk
- A VME chassis contains the following items:
  - ♦ Delta-Tau Systems Inc. 4-axis motion control card with additional 4-axis option
- Two Delta-Tau Systems Inc. 100-watt 4-channel servo amplifiers

- Four CMC DC servo motors
- Three Mirco Mo 1624 motors, and two 1724 motors, all with gearheads
- Infrared heat source from a Conceptronics Pulsar II Rework Station
- 4-axis manipulator mounted on a rugged metal frame
- Conveyor system

3.2.6 Workcell Layout

The overall layout, generated in the preliminary design phase, was for a system containing six modular stations (See ***Figure 1***). The system also includes the operators console and fixture loading area, which is called Station 0. At the end of the system, where the PWA and fixture exit on a conveyor section, is Station 7. The overall length of the system, including Station 0 and Station 7, the system is approximately 28 feet. It is approximately 5 feet from the front of the system to the back (not including the dust collector behind Station 2).

3.2.7 Computer Architecture And Communications

A block diagram of the PWA Repair Facility is shown in ***Figure 4***. Communications between stations is accomplished via ETHERNET Local Area Network (LAN). The Supervisory Computer, at Station 1, contains a large 1.3 GB disk containing all database files such as process parameters, Repair Files, and History Files. Each of the other stations in the system can access the database through the UNIX Network File System (NFS). The Supervisory Computer uses remote program execution and software signals to initiate process programming at each station. The process computer, at each station, returns status information and error conditions to the Supervisory Computer for display on the operators console. In this way, the operator can monitor the progress of each PWA in the system, and is immediately notified of any condition requiring his/her attention.

3.2.8 Robot Specifications

Each station in the system is built on a basic, custom built, modular assembly consisting of a rugged base weldment (See ***Figure 5***), a three axis manipulator for the X, Y, and Z dimensions (See ***Figure 6***), a conveyor system, control hardware such as motors, amplifiers, encoders, digital I/O, and limit switches. To this basic building block is added, other axes, and end-effectors with process equipment, as required, to perform the functions required in each station.

Station 1 contains the basic three axis manipulator (X,Y,Z) which has an overall accuracy of ±0.005". Three CMC DC servo motors provide the motive power for the axes.

Station 2 contains the basic three axis manipulator. It has an additional rotary axis that is powered by a CMC DC servo motor. It is used to move the micro-abrasive blasting nozzle to the 0°, 90°, 180°, and 270° positions corresponding to the four sides of a component. The overall accuracy of this manipulator is ±0.005".

Station 3 contains the basic three axis manipulator, and five additional motion axes (total of eight). A rotary axis, powered by a CMC DC servo motor, moves the end-effector so that the gripping jaws are aligned at the diagonal corners of the component. One motion axis, on the manipulator, controls two Micro Mo 1724 motors. These motors move the gripping jaws and control the size of the aperture. One Micro Mo 1624 motor controls the rectangular shape of the aperture. Two motion axes, each powered by Micro Mo 1624 motors, control the eccentric lifting action required at Station 3. The overall accuracy of this manipulator is also ±0.005".

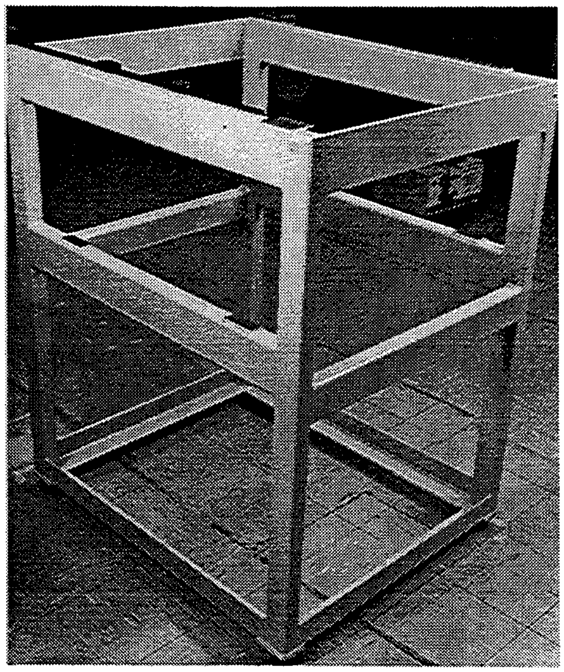

Figure 5. Base Weldment, Rugged Welded Frame to Mount Manipulator.

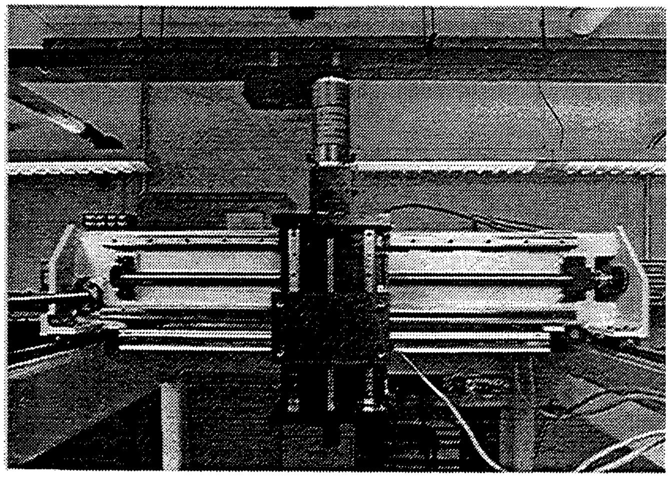

Figure 6. Basic Three Axis Manipulator (X, Y, Z Axes).

3.2.9 Robot Controller

The controller, for all station manipulators, consist of either one or two pair of Delta-Tau Systems Inc. 4-axis motion control cards (VME bus) and 100-watt 4-channel amplifiers with power supplies (See ***Figure 7***). Encoder inputs and end-of-travel (EOT) limit switches are connected to the motion control cards. These cards also contain 16 bits of general purpose digital I/O, which control items such as conveyors, fixture clamping pneumatics, lighting, abrasive blasting pressure and angle, and desoldering power levels.

Robot control programs were developed on an IBM PC and downloaded to the motion control cards via RS-232 serial line. The programs were written in Delta-Tau's PMAC programming language.

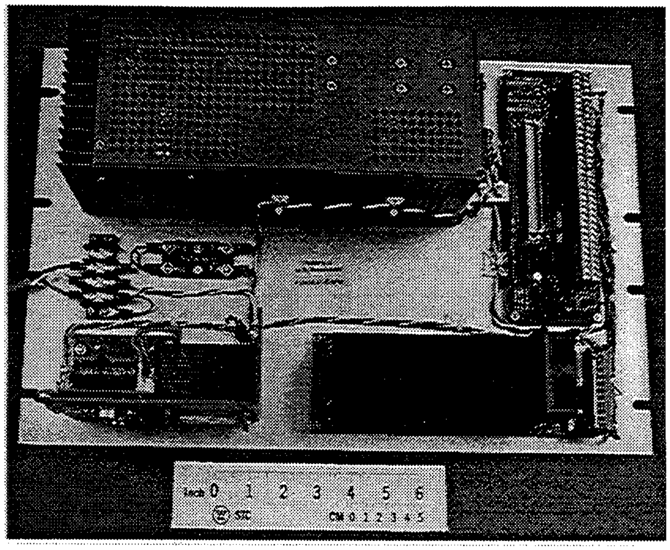

Figure 7. Manipulator Motion Control Hardware. 100-Watt 4-Channel Amplifier and Power Supplies.

3.2.10 Vision Processors

Stations 1 and 2 each contain a state-of-the-art, high speed machine vision system, consisting of Datacube's MaxVideo 20 and Digicolor image processors. These are both VME Bus cards that are programmed from and communicate with the station process computer (Sun SPARCStation) via an S bus to VME bus adapter.

The MaxVideo 20 packs 14 modules on a single card. This modularity allows the programmer flexibility in selecting which functions are needed for a specific application. MaxVideo functions include: acquisition, display, image memory, arithmetic and logic operations, and frame, neighborhood, and point processing. The MaxVideo 20 processing elements and data pipelines operate at 20 MHz which provides the capability to handle 60 frames (512 x 512) per second.

Working in concert with the MaxVideo 20, the Digicolor card provides the capability of a full color imaging system. It can process the Red, Green, and Blue (RGB) signals at 10 MHz so that it can handle 30 full color frames (512 x 512 x 24) per second.

Both modules are programmed using Datacube's ImageFlow software which allows operations to done at frame rates. ImageFlow consists of a library of C language functions for creating pipelines, setting element attributes and controlling data flow through the pipelines.

3.3 System Fabrication And Software Development

Due to the modular nature of the PWA Repair Facility, many of the fabrication and software development tasks could be accomplished in parallel. As the fabrication for Station 1 was being completed, and the software development for that station was started, the fabrication of the other stations could take place. Design modifications, due

to hardware problems that were resolved in Station 1, were then easily incorporated into the other stations as they were fabricated.

3.3.1 Basic Station Fabrication Process

Each station followed the same basic steps in their fabrication procedure. These steps are outlined below.

1. The X-axis rails, motor, and drive screw were mounted to the base weldment.
2. The Y-axis saddle assembly (motor, rails, drive screw) was mounted on the X-axis.
3. The Z-axis assembly was mounted to the Y-saddle.
4. Cabling, wire-ways, and pneumatic connections were added.
5. The X-, Y-, and Z-axes were aligned with a Renishaw laser alignment device. Any nonuniformity in axis motion was measured and stored in data tables. These data are used to correct commanded positions and bring manipulator accuracy to less than ±.005".
6. Individual station additional axes, end-effector, and process equipment were mounted.
7. Station computer, VME chassis and cards, motor drives, system electronics (power supplies, relays, wiring, terminal blocks, etc.) were mounted in the lower part of the base weldment.
8. The conveyor and associated pneumatics were mounted.
9. Cabinetry items, such as panels and front and rear door assemblies, were mounted.

3.3.2 Software Development

The software development process was also modular in nature. The software for each station, and the subsystems within each station, was coded, compiled, and tested independently before integrating and testing the entire system. The vast majority of the software was developed in C on the Sun SPARCStations. However, there were a few exceptions. The motion control code was written using Delta Tau's PMAC programming language. The programming interface, purchased with the MIDAC spectrometer, was written in Array Basic. The following list briefly describes the major software modules for the operations at each station.

- **Station 0**
  - **Operator Interface -** The operator interface was built using Sun's Open Windows Developers Guide which provided the tools (windows, buttons, pull-down menus, sliders, etc.) that are common to many X-based graphical user interfaces. Routines within the Operator Interface acted as the workcell controller by maintaining the database, keeping track of the PWAs currently in-work, activating software programs on the station computers, and displaying system status.
- **STATION 1**

- **Station 1 Main Program -** This is the supervising task for Station 1. When activated by the Supervisory Computer, it executes a sequence of programs to perform each of the operations at Station 1.
- **Index Conveyor -** This program turns on the conveyor, at Station 1, moves the fixture containing the PWA into position, and locks the fixture in place.
- **Component ID and Targeting -** This program uses the Datacube ImageFlow library. It performs all of the functions described in Section 2.6.1.
- **Conformal Coating ID -** The Station 1 Main Program activates this task on the Texas Microsystems PC (connected to the Sun SPARCStation over a bus interface). This task directs the spectrometer to take a measurement and return the result. The result, the generic type of the coating, is stored in the database on the Supervisory Computer.
- **Z-Height Measurement -** The Station 1 Main Program activates this task on the Texas Microsystems PC. This task takes a series of readings from the Cyberoptic laser sensor. These readings are stored in the database on the Supervisory Computer.

- **STATION 2**

- **Station 2 Main Program -** This is the supervising task for Station 2. When activated by the Supervisory Computer, it executes a sequence of programs to perform each of the operations at Station 2.
- **Index Conveyor -** This program turns on the conveyor, at Station 2, moves the fixture containing the PWA into position, and locks the fixture in place.
- **Fluorescence Check -** This program uses the Datacube ImageFlow library. It moves the manipulator to the component to be removed, turns on the UV light, and takes an image of the coating. Thresholding algorithms determine if the coating fluoresces. The result is stored in the database on the Supervisory Computer.
- **Conformal Coating Removal -** This program reads the database, on the Supervisory Computer, for the coating removal parameters and the coordinate data of the coating removal area. It turns on the abrasive blaster and directs the nozzle over each segment of the removal area with a back-and-forth motion.
- **Check For Remaining Coating -** This program uses the Datacube ImageFlow library. It analyzes each segment of the coating removal area, and determines the amount of coating that remains. The results are stored in the database so that the Station 2 Main Program can decide to reiterate the coating removal process.

- **STATION 3**

- **Station 3 Main Program -** This is the supervising task for Station 3. When activated by the Supervisory Computer, it executes a sequence of programs to perform each of the operations at Station 3.
- **Index Conveyor -** This program turns on the conveyor, at Station 3, moves the fixture containing the PWA into position, and locks the fixture in place.

- **Desolder and Component Removal -** This program reads the database, on the Supervisory Computer, for the desoldering parameters and coordinate data of the component location. It moves the end-effector to the component and turns on the IR heat source at the Preheat power level. After the Preheat time interval is expired, the IR heat source is switched to the Reflow power level. After the Reflow time interval has expired, the jaws are moved to grasp the component. The current, drawn by the jaw motors, is monitored until there is a significant increase. At this point the component is firmly grasped, and the two lifting motors are activated. The manipulator then moves to the "nest" on the fixture, and the component is deposited there.

3.3.3 System Integration

Prior to system integration, each of the individual stations had been tested and debugged. During integration, the stations were physically adjoined and tested as a single system.

3.3.3.1 Vision Calibration Procedure

One of the main tasks during integration was implementing a vision calibration procedure at Station 1. This was needed in order for location coordinate data, gathered during the component targeting operation at Station 1, to be valid at the other stations. The procedure involves taking images of a special calibration fixture. Calibration features, of known size and spacing, were precision machined into the fixture. The vision system, at Stations 1 and 2, measures these features to get calibration constants (pixels/inch in X,Y) that are subsequently used in component targeting operations. This same fixture is also used to generate a base frame (homogeneous coordinate transform matrix) that relates the fixture to the robot manipulators.

3.4 Database Concerns

The database requirements of the PWA Repair Facility are not large or complex. Several commercially available relational database management system (RDBMS), such as Empress, Interbase, Progress, Sybase, and TekBase were evaluated. Since the database requirements were modest and the price of these systems were high ($4000 to $5000 per node x 6 nodes + $6000 to $8000 for a development license) RDBMS software was considered to be an "overkill" for this system. Therefore, a set of individual data files are used to meet the needs of the system. These files fall into one of the following categories:

1. **Repair Files -** There is a separate Repair File for each individual component repaired by the PWA Repair Facility. This file is identified by PWA Part Number, Serial Number, and Component ID. It contains the PWA Core Type, Lead Type, Lead Pitch , Number Leads, all of the component's location data, and process status information from each station. This file is not kept in permanent storage. Once a component completes processing at all stations, and the Repair Report is printed (See Repair Report File), then the file can be deleted.
2. **History Files -** There is a separate History File for each PWA type and component that has been processed by the PWA Repair Facility. This file is identified by PWA

Part Number and Component ID. It contains much of the same data as the Repair File except for the process status information from each station. It is used to simplify some of the operations involving operator input at Stations 0 and 1. For example, if the same component, U102, on PWA Part Number 717612444-011, were to be repaired on multiple copies of that PWA (with different serial numbers), then after the first repair the History File exists. On subsequent repairs of the other PWAs, the operator will not be prompted to enter PWA Core Type, Lead Type, Number of Leads, etc. In addition, the operator can skip all but the first component targeting function at Station 1. History Files are kept in permanent storage, and are not deleted.

3. **Current PWA Data File -** This is a singe file containing a list of all PWAs currently in-work at each station in the PWA Repair Facility. This file is updated whenever the status of a PWA changes, or as PWAs enter, index, or exit the system.
4. **PWA Repair Report File -** There is a separate Repair Report File for each individual component repaired by the PWA Repair Facility. This file is identified by PWA Part Number, Serial Number, and Component ID. It contains additional information such as Operator ID, repair times, and repair status. These files are put in permanent storage for future determination of repair trends.
5. **Parameter Data Files -** There is a single data file for the coating removal, and desoldering parameters. They are updated whenever the parameters are changed using the parameter editing functions (See Section 2.5.2). They are permanent files and are not deleted.

3.4.1 Interface To PLAD System

An interface to the PLAD (Paperless LANTIRN Automated Depot) computer system, was designed into PWA Repair Facility. This interface consisted of a series of messages sent between the PLAD system and the PWA Repair Facility via the TCP/IP network. This allows the PLAD system to initiate a repair in a way similar to the function described in Section 4.1.1, **Initiating The Repair Process**. When a repair is complete, the PWA Repair Facility responds with status information. Although not used at present, future integration with the PLAD system is facilitated.

3.5 Fixturing

The universal locating fixture carries the PWA through each station in the system (See ***Figure 11***). It was designed to easily adjust to accommodate PWAs ranging in size from 1.5" x 1.5" to 16" x 18". It must hold the position of the PWA, within an individual station, to ± .001". The fixture must be located from station to station to within ±.001". This is needed so that the location information, measured in Station 1, is valid at subsequent stations. In addition, it must be rigid enough to withstand the pulling forces at Station 3 (up to 34 lbs.) , and yet be light enough for the operator to easily handle.

The fixture contains four steel reinforced locating holes, two on each side. The fixture enters a station on it's conveyor. It hits a hard stop that is raised and lowered under computer control. At the same time, limit switches are activated causing pneumatic cylinders to push from below and raise the fixture up against locating pins that fit the

locating holes. This way, the fixture is both rigidly locked into position and repeatedly located to within ±.001".

3.6 Safety

The main safety aspect, of the PWA Repair Facility, are the enclosures that surround each station. The enclosures prevent any potentially harmful items, such as laser light, infrared radiation, blasting abrasive, dust, fumes, etc., from exiting the Repair Facility. Conversely, the enclosures prevent any intrusion of personnel into the stations. The key features of the enclosures, are listed below.

1. Each station's enclosure has a set of front and back doors. All doors have a safety interlock that is activated whenever the doors are opened.
2. Whenever a station's doors are opened and the interlock is activated, a software program controlling the manipulators executes the following actions.

   A. Immediately deactivate all end effectors. This includes turning off the following items:

   - The laser sensor at Station 1
   - The abrasive blaster at Station 2
   - The IR heat source at Station 3

   B. If the conveyor is moving, it is stopped.

   C. All manipulator motion axes are temporarily halted.
3. The Cyberoptic laser sensor, in Station 1, is a class IIIb laser. However, because of the surrounding enclosure, it is reduced to a class I laser which presents no biological risk (refer to Federal Performance Standard for Laser Products 21 CFR 1040.10 and 1040.11). With the doors closed, the laser light cannot directly exit the station. With the doors open, the laser is deactivated.
4. On the front doors, of each station, is an emergency stop button for that station. In addition, there is a system-wide emergency stop button at Station 0. They are hardwired directly to the manipulators. When the button is pushed, all motion axes are immediately halted.
5. "CAUTION" placards are in place on the enclosures.
6. Prior to opening the doors to a station, the operator must acknowledge a prompt displayed on the console terminal. A message is displayed when it is safe for the operator to open the doors.

3.7 Validation And Acceptance Test

The PWA Repair Facility validation was performed by exercising the system in the capacity for which it was designed. Although the system consists of separate stations joined by conveyors, testing was accomplished by utilizing the system as a whole in its normal capacity to remove a variety of components. These components included a representative set of devices installed on a test coupon PWA (See Section 3.7.1).

The Validation and Acceptance Test was conducted at Westinghouse STC under the direction of Westinghouse test engineers who acted as system operators. Air Force personnel acted as the verifying person and signed the validation test check lists as each PWA Repair Facility operation was successfully completed. Total station cycle time was noted on the check lists to establish system speed and efficiency. The Validation & Acceptance Test is described in detail in the document titled "Automated Repair Of Printed Wiring Assemblies Validation & Acceptance Test Plan" CDRL 015, 016.

3.7.1 Test Coupons

Validation testing required that a series of PWAs be processed by the system to complete validation testing. Because of the lack of actual Air Force PWAs, such as the LANTIRN board, test coupons were designed by Westinghouse and built by Warner Robins ALC. The test coupons were fabricated to resemble LANTIRN boards in terms of size, rigidity, thermal characteristics, and types of components. The coupons consist of a printed circuit board laminated to a metal core plate. Components were mounted on the printed circuit board. The components used, were "dummy" components, which are packages or chip carriers without the integrated circuit. The test coupons have the following characteristics.

- There were two sets of coupons with five in each set (total of ten). Each set have a coupon with one of the five generic conformal coatings applied to it.
- One set have gullwing devices on each coupon. This device is a Ceramic Quad Flatpack (CERQUAD), 0.95" x 0.95", 0.025" lead pitch, 132 leads. The other set of coupons have leadless devices on each coupon. This device is a Ceramic Leadless Chip Carrier (LCC), 0.45" x 0.55", 0.050" lead pitch, 32 leads. Both of these devices are typical devices found on LANTIRN boards.
- The components were soldered to the coupon and the same thermal adhesive, used on components on LANTIRN boards, was also applied to the components on the coupons.

The validation test was successfully completed using the test coupons. The coupons were useful to develop coating removal parameters used at Station 2, the desoldering and component removal parameters used at Station 3, and to validate the system as a whole. Although the test coupons were designed to be cost effective and yet still resemble LANTIRN boards, the test coupons had several differences when compared to actual LANTIRN boards. The LANTIRN boards contain a wider variety of components than the test coupons. Also, LANTIRN boards have components with leads connected to power and ground planes. This caused those leads to "sink" more energy, requiring longer heating cycles in the desoldering operation than those needed for the test coupons. Therefore, it was necessary to develop additional parametric data once the system was installed at Warner Robins ALC and actual LANTIRN boards were processed by the system.

3.8 Installation At Warner Robins ALC

The completed PWA Repair Facility was dismantled, packed, and shipped to Warner Robins ALC, Avionics Production Division, in July 1994. The system was located

adjacent to the Paperless LANTIRN Automated Depot (PLAD) facility. After initial start-up and verification, the validation test, carried out at Westinghouse STC, was essentially repeated. In the following weeks, operator training was performed.

3.8.1 Validation And Production Testing At WR-ALC

The same validation test, described in Section 3.7, was successfully completed at Warner Robins ALC. Additional copies of the test coupons, used in the test at Westinghouse STC, were used at WR-ALC.

Production testing, using real PWAs supplied by Warner Robins, followed the validation testing, and is on-going at the present time. This testing is used to "fine-tune" process parameters and to provide significant "run-time" in order to completely verify the system.

3.8.2 Follow-up Support

John Lichauer, of Westinghouse STC, has made numerous field service trips to Warner Robins ALC for the purpose of the on-going production testing, operator training, maintenance, and debugging. This support will continue until contract requirements are satisfied.

4. SYSTEM OPERATION

4.1 Station 0 - Operator Control

The operator, positioned to the left of the system--called Station 0, uses a console terminal (monitor, keyboard, and mouse) and a video monitor for viewing camera images from the stations (See ***Figure 8***). This constitutes the entire operator interface to the PWA Repair Facility. From this location the operator initiates, controls, and monitors the repair process.

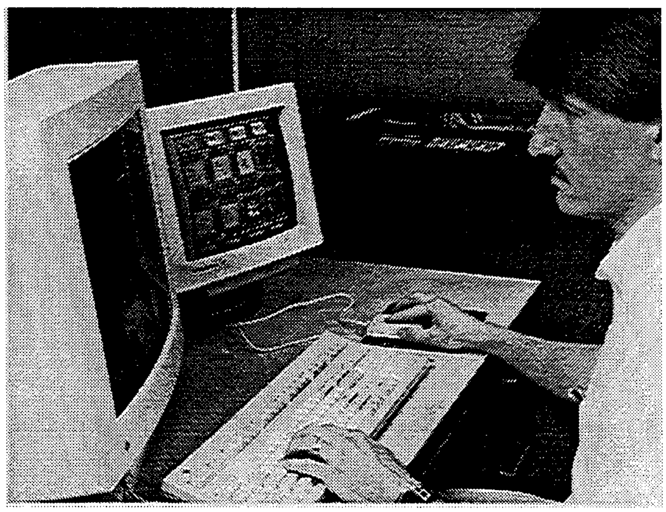

Figure 8. Station 0 - Operator Console Terminal & Video Monitor.

4.1.1 Initiating The Repair Process

Initiating the repair process is a two step procedure. The operator enters the following information (See ***Figure 9*** and ***Figure 10***):

PWA Part Number - Alphanumeric string that identifies the type of PWA

PWA Serial Number - Numeric string that uniquely identifies a specific PWA of the type specified by the Part Number.

Component ID - Alphanumeric string identifying the component, on the PWA, to be removed. Examples are U102, U19, etc.

Lead Type - The operator selects one of the lead types, listed in Section 2.3, from a menu.

PWA Core Type - The operator selects one of the four PWA Core Types, listed in Section **2.2.1**, from a menu.

Coating Removal Work Angle - The operator selects either 0° or 45° for the work angle used for coating removal at Station 2. This decision is based on the height of components adjacent to the defective component. Taller adjacent components require the steeper (0°) work angle.

Station 3 Gripper Tip Type - The operator selects either Picture Corner or Notched Corner depending on the corner geometry of the component to be removed.

Component Removal Temperature Settings - The operator enters the Preheat and Reflow Temperature (Percent of full lamp power), and Time duration (sec.) settings used in the desoldering operation at Station 3.

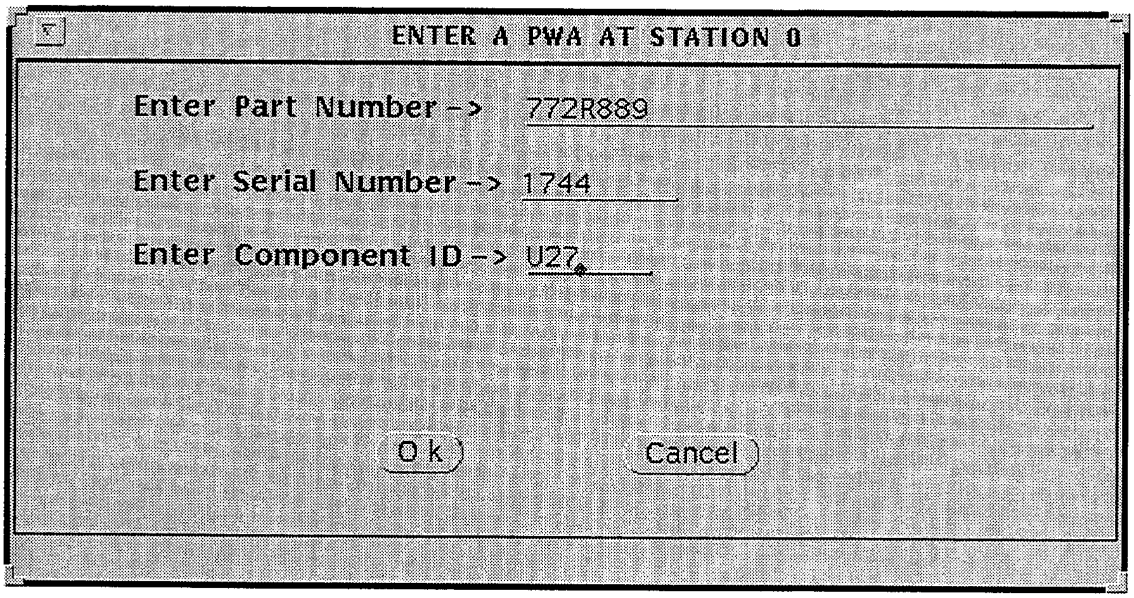

Figure 9. Initiating the repair process (step 1), the operator enters the PWA Part Number, Serial Number , and Component ID.

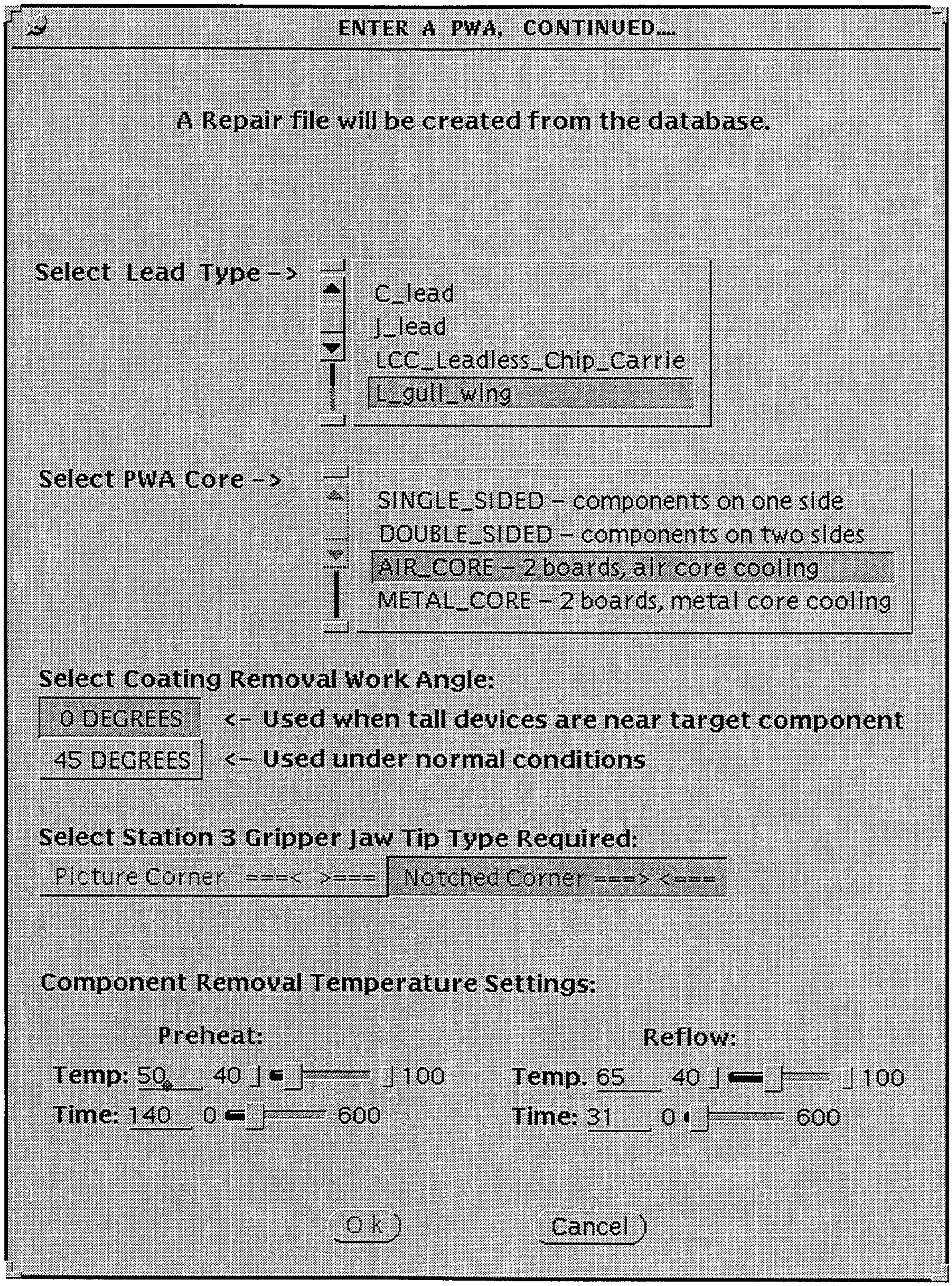

Figure 10. Initiating the repair Process (step 2), the operator enters Lead Type, PWA Core Type, Coating Removal Work Angle, Gripper Jaw Tip Type, and Temperature settings used at Station 3.

After this information is entered, the operator is prompted to load the PWA into a universal locating fixture (See ***Figure 11***) that rigidly holds the PWA and carries it through each station via the conveyor system. The fixture is placed onto the conveyor leading into Station 1 (See ***Figure 12***). The operator is provided with the PWA Status and Control Window (See ***Figure 13***) that displays, in a simple table format, the PWAs currently under repair at each station.

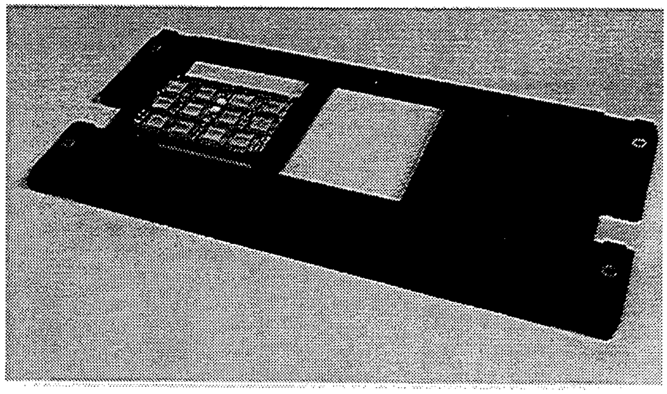

Figure 11. PWA Universal Locating Fixture. PWA Installed and Rigidly Clamped.

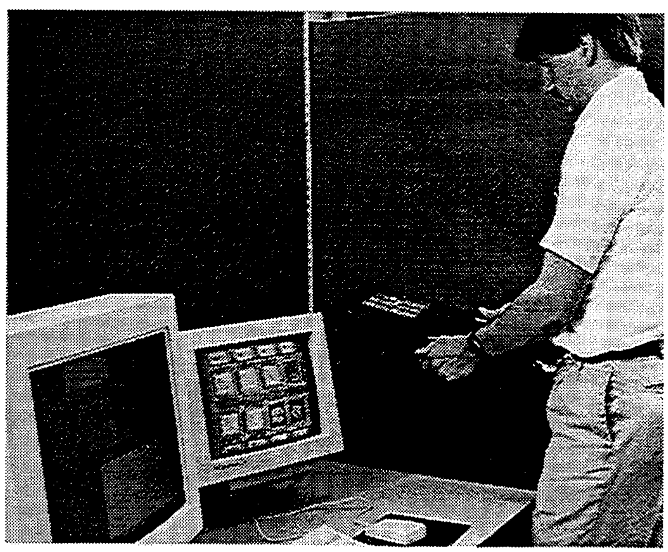

Figure 12. Operator Inserting Fixtured PWA Into System. Operator Sets the Fixture Onto Rollers Leading To Conveyor.

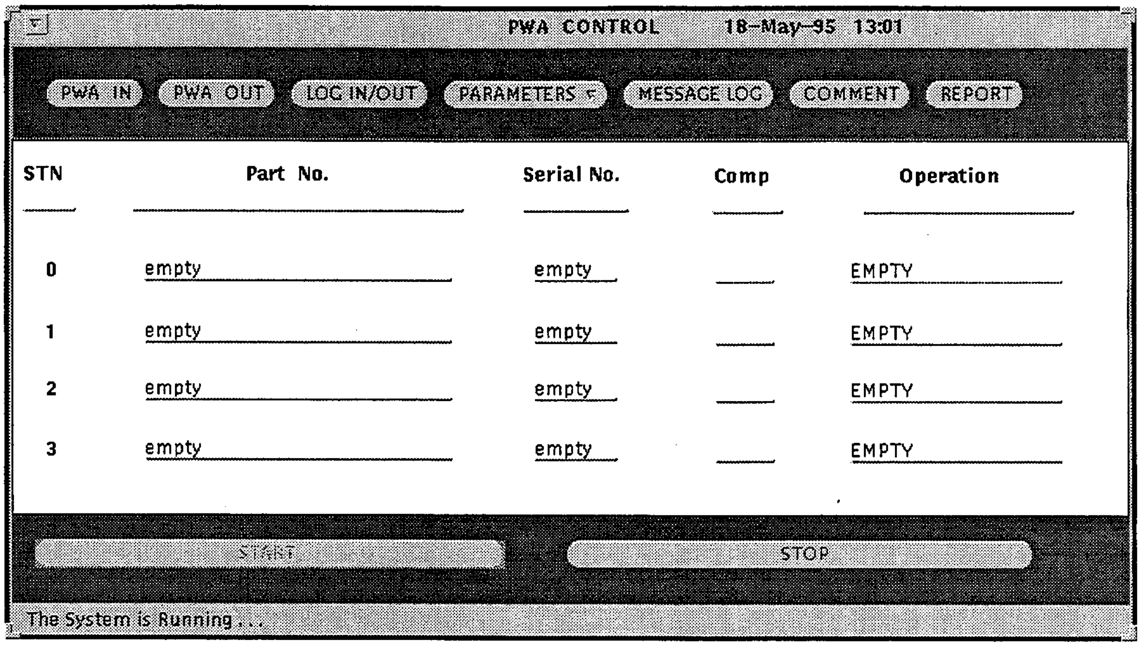

Figure 13. PWA Status and Control Window.

4.1.2 Process Control Parameters

The Operator Interface also includes the ability to modify process parameters used in each station. These parameters control operations such as Coating Removal, Desoldering, Solder Paste Deposition, etc. An example of a parameter edit window is shown in ***Figure 14***. This allows for adjustment of the repair process as component and PWA requirements change in the future. Access to the parameter editing controls is granted according to operator privilege level, so that only engineering or process/quality personnel can change the parameters.

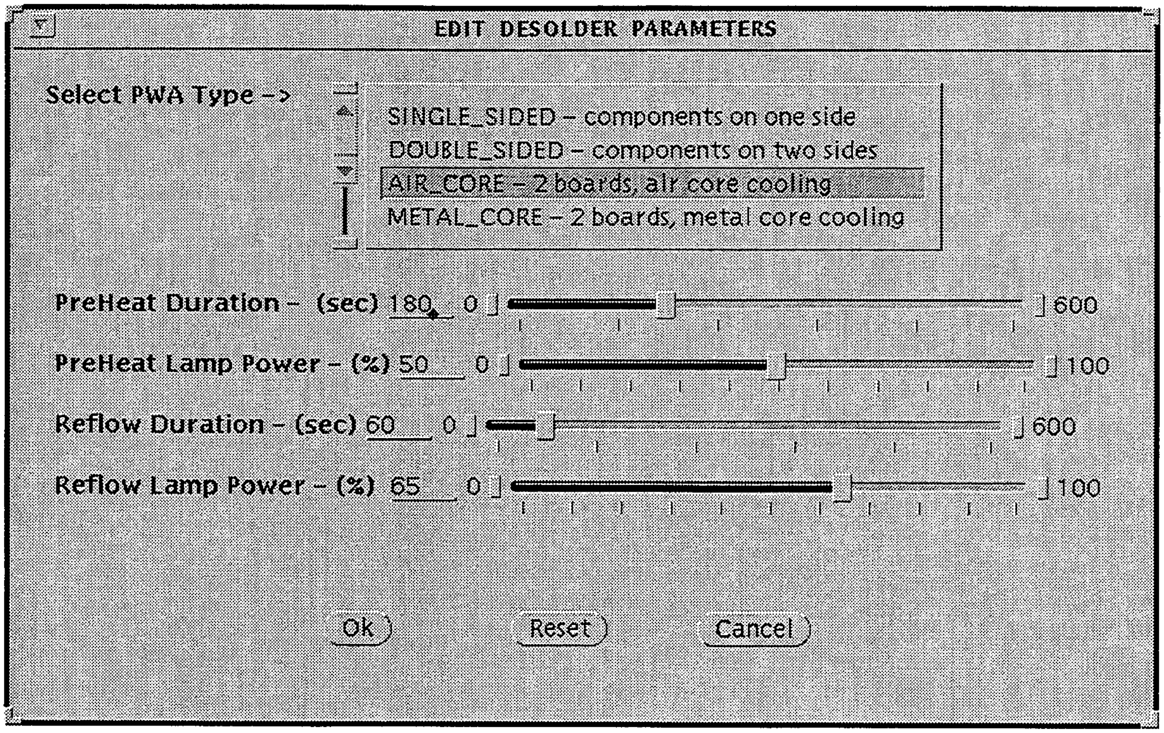

Figure 14. Typical Parameter Setting Window.

4.2 Station 1 - Component Identification And Targeting

In Station 1, the component to be removed is identified, its location coordinates determined, the coating removal area specified, the PWA surface height is measured, and the conformal coating is identified. ***Figure 15*** and ***Figure 16*** show the details of Station 1.

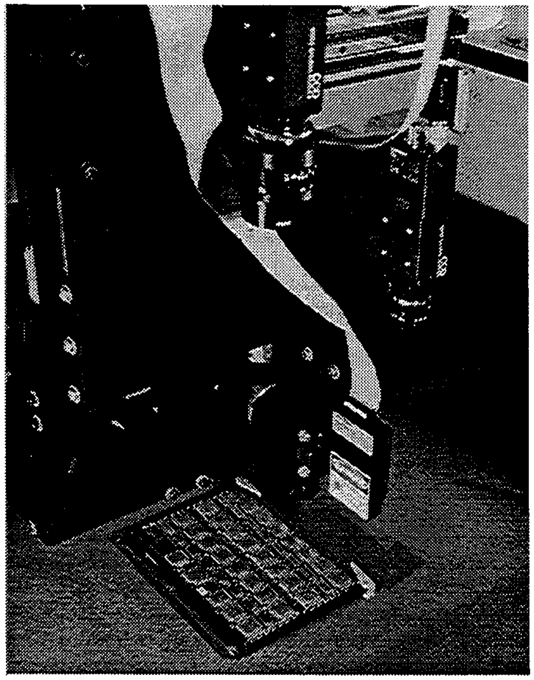

Figure 15. Station 1 Front View. Close-up of Sensors.

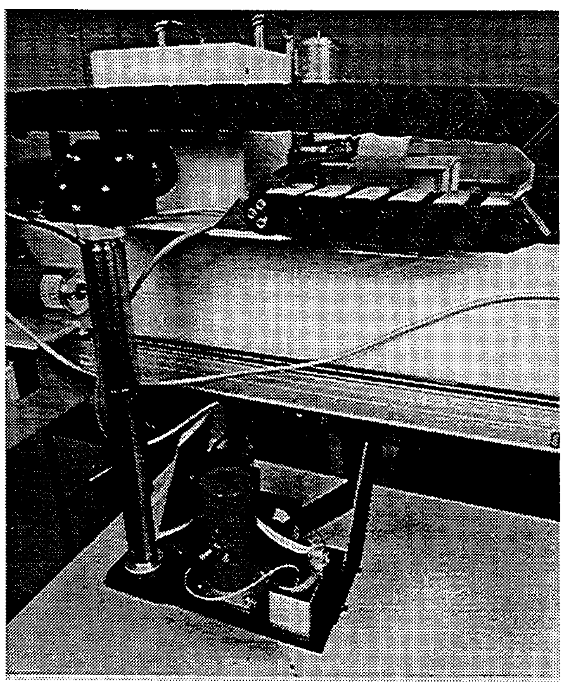

Figure 16. Station 1 Rear View. Spectrometer, Telescoping Beam Delivery Tube, and N_2 Dewar.

4.2.1 Component Targeting Operations

The first operation, in Station 1, is component targeting. It is how the defective component is identified to the PWA Repair Facility. Due to the wide variety of component geometries, of component polarity features, and structures such as small capacitors, solder pads, etc., that are adjacent to the defective component, a fully automatic component targeting operation would require a very complex and extensive set of image processing algorithms. In addition to being costly, a fully automatic targeting operation would not be as flexible as the existing, operator-assisted operation. It is a semi-automatic operation requiring the operator to visually locate the component. A dedicated machine vision system, a pair of cameras, and a video monitor assist the operator in identifying and locating the defective component.

When the PWA enters the station, and the fixture is locked into position, then the component ID and location window automatically appears on the operator's console terminal. This window provides a set of controls that lead the operator through a step-by-step procedure for identifying and locating the defective component (See ***Figure 17***). The steps in the component targeting operation are described below. The operator can repeat any step until the desired results are achieved.

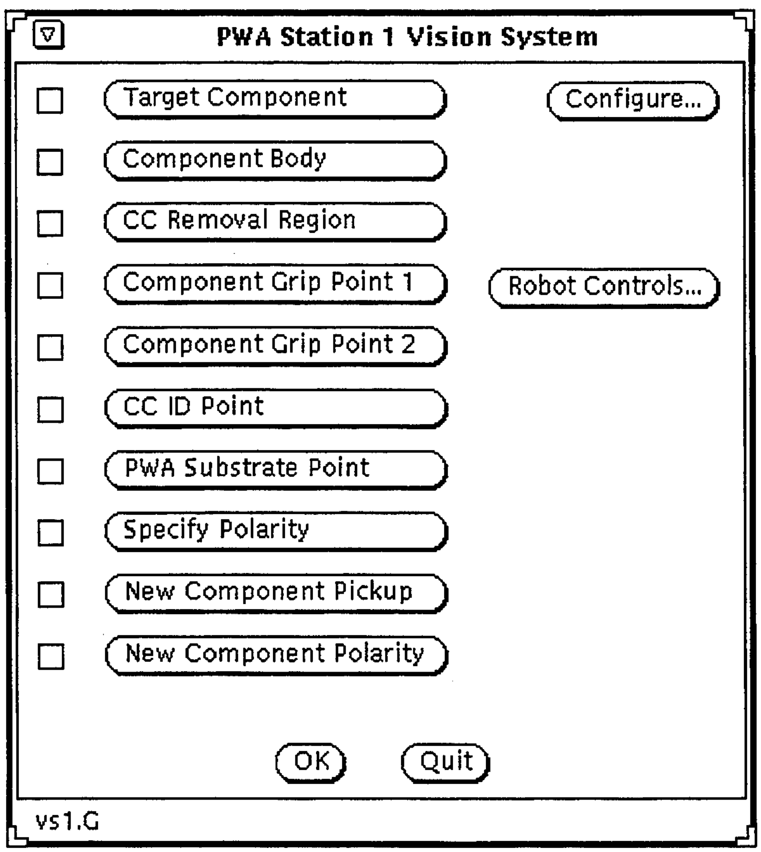

Figure 17. Component Identification and Targeting Window.

1. **Target Component -** This is a two-phased operation that specifies a coarse location of the PWA and component. The specifications of the PWA Repair Facility require

the system to process PWAs as large as 16" x 18", and components as small as 0.05" x .1". For the operator to be able to easily see the smallest component, the macro camera must have a field of view no larger than 8.25" x 11.0". Therefore, the work area in Station 1, is divided into four overlapping quadrants. First, the operator selects the quadrant containing the PWA/Component. The manipulator moves so that the macro camera is centered over that quadrant, and a magnified view of the quadrant is presented to the operator on the video monitor. The resolution of the image from the macro camera is 0.0145" per pixel. The operator then uses the mouse to "drag" a box, in the video image, over the area containing the defective component. This box represents the field of view of the micro camera (approximately 2.5" x 2.5"). The manipulator moves the micro camera to the area specified by the operator and a close-up view of the defective component is displayed in the video monitor. The resolution of the image, from the micro camera is 0.0045" per pixel. With this resolution, the operator can accurately position a cursor to complete the remainder of the component targeting operations.

2. **Component Body -** The operator looks at the magnified view of the component from the micro camera. The resolution of this image is 0.0045" per pixel. With this resolution, the operator can accurately locate the component body. The operator uses the mouse to position a cursor at one corner of the component, then "drags" a stretch box to the opposite corner of the component. This box defines an accurate location of the component.

3. **Conformal Coating (CC) Removal Region -** Conformal coating must be removed from an area surrounding the defective component's body. The coating must be completely removed from the component's leads or solder points. The inner boundary, of the removal region, is the component body rectangle specified in step 2 Component Body. The outer boundary of the coating removal region is specified in this step. The operator uses the mouse to position a cursor at a point outside the first corner specified in step 2 Component Body. The operator "drags" a stretch box to a point outside the second corner specified in step 2. When this is completed, a second rectangle, larger than the first one specified in step 2, is created by the operator. The area between the two rectangles is the conformal coating removal region.

4. **Component Grip Point 1 -** This function is used to specify the location of one corner of the defective component, where the gripping device used at Station 3, is to grasp the component. The operator looks at the magnified view of the component from the micro camera. The operator uses the mouse to move a cursor to accurately locate the desired corner. In general, the corner with the component's polarity feature is not used since its geometry is different than the other three corners. When the corner is located with the mouse, a small crosshair graphic appears at that location.

5. **Component Grip Point 2 -** This function works the same way as Component Grip Point 1. However, it is used to specify the location of the opposing corner of the defective component, where the gripping device in Station 3, grasps the component. The gripping device grasps the component at the two opposing corners.

6. **Conformal Coating (CC) ID Point -** This function is used to specify a coarse location, on the component's body, that is used to identify the conformal coating. The operator looks at the magnified view of the component from the micro camera. The operator uses the mouse to move a circular cursor (representing a 1/8" diameter area) to a location on the component where conformal coating is identified.

7. **PWA Substrate Point** - This function is used to specify a point, on the PWA, that is used to measure the height (Z coordinate) of the PWA surface. This point is near the defective component where the surface of the PWA is visible. The operator must select a location on the PWA surface, not on a small adjacent component such as a capacitor, or on a solder pad, etc. This is done to get an accurate Z-height measurement so that the gripping device, at Station 3, can be placed accurately. The operator looks at the magnified view of the component from the micro camera. The operator uses the mouse to position a circular cursor at the PWA surface point.

8. **Component Polarity** - This function is used to specify the polarity of the defective component. The polarity is the feature, on the component body, that designates lead number 1. This feature varies greatly from one type of device to another. Specifying the polarity is necessary so that a replacement component can be positioned in the same orientation as the defective component. The operator looks at the magnified view of the component from the micro camera. The operator uses the mouse to position a circular cursor near the polarity feature on the component, usually near one of the corners of the component's body.

NOTE: All of the component targeting functions, except 1. Target Component, can be skipped by the operator if the target component and PWA are in the History Database (See Section 3.4). The locations of the targeting graphics will be retrieved from the database and overlaid on the image presented to the operator. The operator has the opportunity to confirm their accuracy.

4.2.2 PWA Surface Height Measurement

In the previous section, Component Targeting Operations, various locations are specified by the operator looking at an enlarged view (from the micro camera) of the component, and using the mouse to point to these locations. This establishes a location in a horizontal plane (X, Y coordinates). To get a complete 3-D location (X, Y, Z coordinates), required by the manipulators, the Z coordinate of the component body, PWA surface, and coating ID location, must be measured. The Cyberoptics Point Range System (PRS) noncontact laser sensor is used for this purpose. The manipulator moves the sensor to each location to be measured. The sensor measures the distance, to the object under the laser, with an accuracy of ± .004". The Z coordinate is then calculated and stored in the database.

4.2.3 Conformal Coating Identification

The last operation at Station 1 is conformal coating identification. The coating is identified as one the five generic coatings listed below.

- **ACRYLIC**
- **EPOXY**
- **PARAXYLENE**
- **POLYURETHANE**
- **SILICONE**

The conformal coating must be identified so that the proper coating removal parameters are used at Station 3. The removal parameters are much more aggressive for a hard coating, such as epoxy, than those used to remove a soft coating such as silicone. Using the wrong removal parameters, at Station 2, could cause the PWA to be damaged beyond repair.

The MIDAC FTIR Spectrometer and Axiom detector were used for this purpose. They provide a real time non-contact means for identifying the conformal coating on the PWA. It samples the reflected IR signature, of the coating on the PWA, with the signatures listed in it's reference library. It then returns a result, which is the generic category of the coating in the library that is the best match to the measured coating.

4.3 Station 2 - Conformal Coating Removal

Prior to desoldering, the conformal coating must be completely removed from all solder points on the defective component. If this were not done, the coating would hinder the desoldering operation at Station 3, both in component gripping and solder cleanup. Even though the old solder is to be removed, and new solder deposited, any residual coating left on or near the pad can contaminate the new solder and cause a poor solder joint in the new component.

4.3.1 Coating Removal Process

Station 2 uses precise computer control of the blasting operation and the iterative process of blasting and examination, to eliminate concerns of damage to the PWA. A Ultra-Violet light source coupled with a machine vision system allows the blasted area to be checked repeatedly for coating remaining.

The first operation at Station 2 is fluorescence check. The manipulator automatically moves the CCD camera over the area where coating will be removed. A UV light source is turned on and the vision system determines whether or not the coating fluoresces (See ***Figure 18***). If the coating fluoresces, the coating removal operation is fully automatic. Based on the type of coating identified in Station 1 and the outline of the component defined by the operator, parameters are set for blasting pressure, stand-off distance, travel speed, and work angle (either 0° or 45°). A separate set of parameters exist for the initial pass and for the follow-up passes. After the first pass is completed, a check is made by the vision system to determine if coating remains. The process is repeated until the coating is removed. If the coating does not fluoresce, bright white lights are turned on within the station and the area is displayed on the video monitor. In this case, the operator specifies which parts of the removal area require additional blasting. MIL Spec conformal coatings contain a fluorescent tracer. ***Figure 19*** and ***Figure 20*** show details of Station 2.

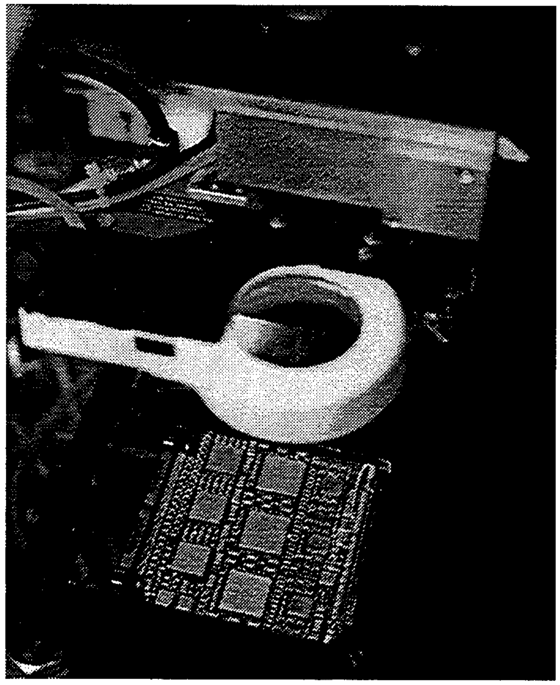

Figure 18. Close-up of UV Light Source at Station 2. A Machine Vision System Determines Whether Or Not the Coating Fluoresces.

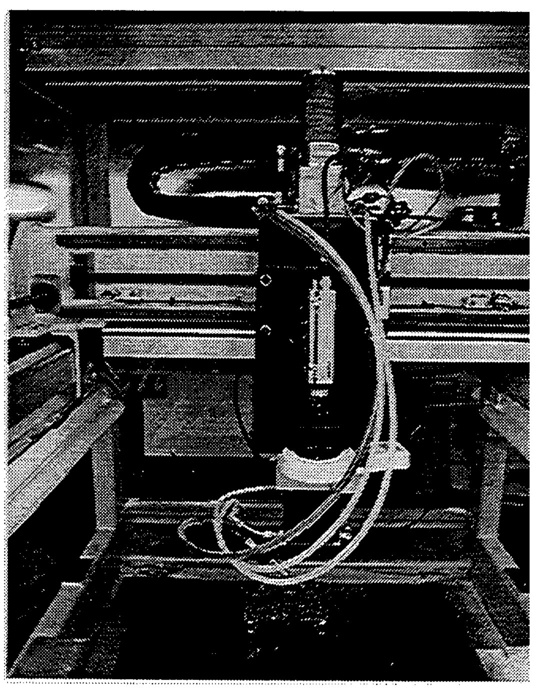

Figure 19. Station 2, Overall View of Coating Removal System.

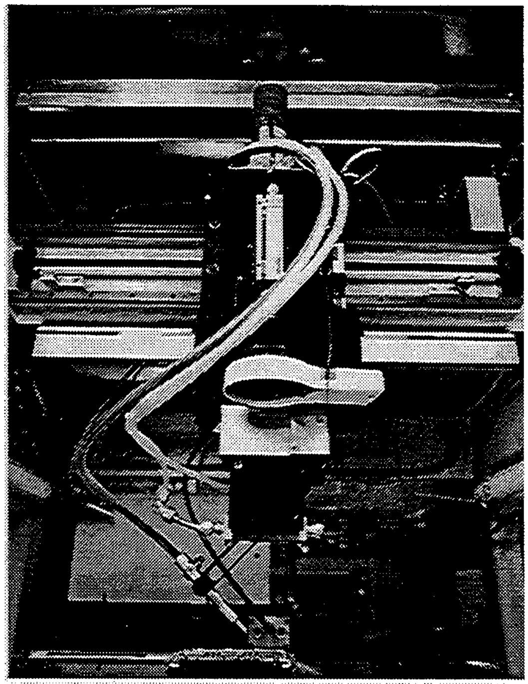

Figure 20. Station 2, Close-up of Abrasive Blasting Nozzle and UV Light Source.

4.4 Station 3 - Desolder And Component Removal

ANSI publication *Suggested Guidelines for Modification, Rework and Repair of Printed Boards and Assemblies (ANSI/IPC-R-700C)* states: "It is desirable for SMD removal and Removal & Replacement (R&R) systems to have a controlled process of concentrated selective heating, controlled bond shear and lift off, and accurate positioning and placement of the replacement leadless, short leaded and long leaded SMDs by removing human factors from SMD removal and R&R process, and making the SMD removal and R&R a repeatable process." It goes on to say: "The ultimate goal for SMD removal and R&R is to limit the application of heat to the component being removed and replaced, and to minimize (eliminate) the application of heat to other components in the local area." The following sections describe how Station 3, of the PWA Repair Facility, implements these guidelines in its component removal process.

4.4.1 Desoldering Process

Station 3 desolders and removes the defective component from the PWA. Conventional methods, used by commercially available manual rework stations, involve vacuum pickup of the component when solder melt temperatures are reached. However, some PWA components are bonded with adhesive compounds both for mechanical strength and for thermal transfer to the PWA substrate. Some adhesives completely break down under desoldering temperatures, however some do not. In the manual repair process, an operator uses a tool, such as a screw driver, to pry and twist at one corner of the component to break it free. There is risk of doing damage to the PWA with this method and a means to automatically lift the component was developed.

Also, in order to minimize the risk of damage to the PWA, only the defective component must be heated. Again, conventional methods rely on hot gas or contact heating tools with heads selected to fit the component. Even rework stations, that use an IR beam to heat the component, require different lenses and apertures to remove devices of various sizes. These methods rely on manual intervention from skilled technicians, and can lead to inconsistent results.

The operations, at Station 3, require an end effector consisting of a collimated IR heat source, coupled with a controlled set of gripper jaws. Additional motion axes automatically align the grippers and control the size and shape of an aperture on the desoldering heating system. Additional drives grip the component for removal and apply a lifting force.

4.4.2 Heating Cycles For Adhesive Breakdown

The process at this station begins when the desoldering end effector is located over the component to be removed. Based operator inputs at Station 0, and location data generated at Station 1, the aperture is adjusted to closely match the size and (rectangular) shape of the component. The collimated IR beam passes through the aperture to provide local heating to the component. The desoldering heat cycles were developed based on component size and type of PWA. The Preheat Cycle begins with a reduced level of IR energy to allow the temperature of the PWA to rise within prescribed limits to minimize thermal stresses to the PWA. After a timed interval, the Reflow Cycle begins and the heat source is switched to a higher level. At this level, two events must occur. First, the solder at all leads must be completely melted. Secondly, the adhesive must be sufficiently broken-down to allow component removal.

4.4.3 Component Gripping And Lifting

Near the end of the Reflow Cycle, the set of gripping jaws that are prepositioned at two diagonal corners of the component, are activated. They grasp the component and a lifting force is applied to one corner. It was determined that this eccentric pull on the component provides tensile fracture which propagates across the adhesive bond between the component and PWA. The forces required to break the adhesive bond in this manner, are much less than if the pull forces are applied normal to the PWA. After the component is removed, it is deposited in a "nest" on the fixture. ***Figure 21*** and ***Figure 22*** show details of Station 3.

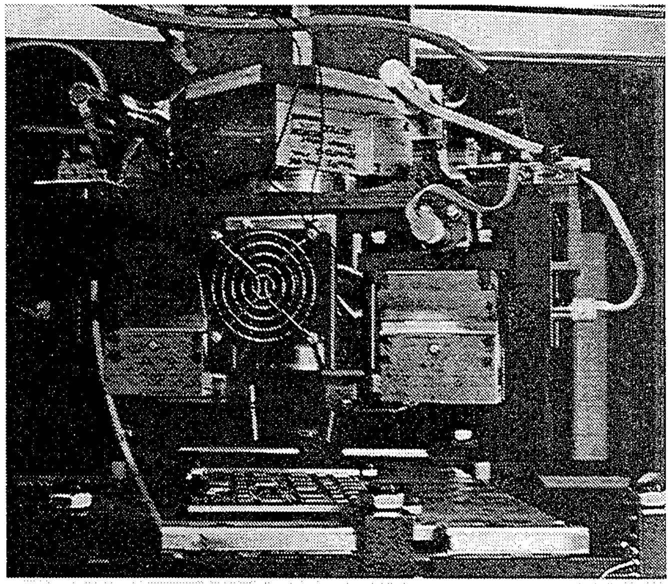

Figure 21. Station 3, View of Component Gripper Assembly.

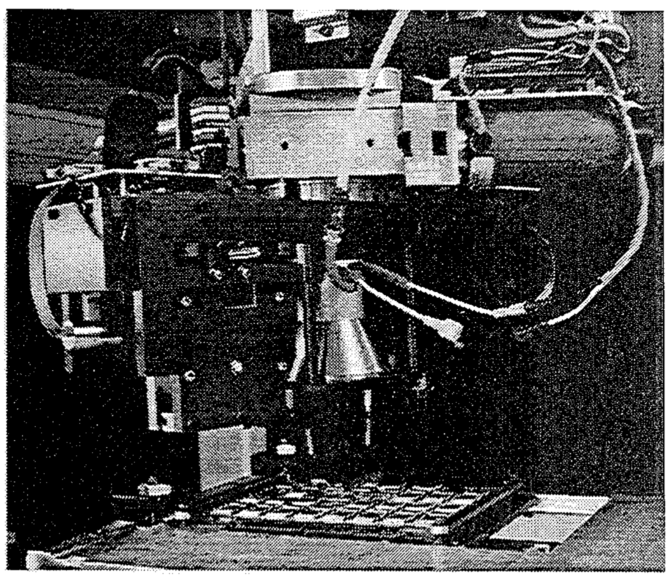

Figure 22. Station 3, View of IR Heat Source.

5. FUTURE APPLICATIONS

The PWA Repair Facility can repair a variety of avionics printed wiring assemblies that previously may have been repaired, but with great difficulty and risk of damage to the PWA. The Needs Analysis (See Section 3.1.1) points out that conservative estimates of future PWA repair needs show considerable cost saving by employing a repair facility that can repair assemblies that otherwise would be scrapped due to the inability to be repaired manually. The Needs Analysis did not factor in the added cost of disposing of scrap PWAs in an environmentally safe way. In addition to cost savings, the PWA Repair Facility could also be utilized in the following applications:

- Commercial (nonmilitary) automatic rework - existing, commercially available, rework stations are semi-automatic in nature involving a high degree of operator skill. The PWA Repair Facility is an automatic system that can provide a much more complete, consistent, and repeatable repair process.
- Conformal Coating Removal - Because of its modular design, the conformal coating removal operation could easily be separated into two, or even a single station. The controlled, nondestructive abrasive blasting technique for coating removal is not found in commercial rework stations. Several parties, such as the U.S. Navy and Ford Motor Company, have expressed interest in this application.
- Visual Inspection - with the advanced machine vision systems, used in the Repair Facility, algorithms could be written to automatically inspect PWAs for defects such as bent or lifted leads, delamination of conductive patterns (lands, conductors, through holes, etc.), blisters, measiling, crazing, haloing, fiber exposure, etc.